THE ARCHIVES OF TRANSPORT

VOL. XXII NO 3 2010

10.2478/v10174-010-0018-x

Issues Related to the Optimization of Location of Vehicle Recycling Network Entities

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Received November 2010

Abstract

The paper presents issues related to the optimization of the location of the entities that belong to the end-of-life vehicle recycling network. A structure of the network has been presented, the criteria of optimization have been defined and the factors that have impact on the selection of the entities while designing the network have been listed. The paper also presents a formulation of an example optimization task in the aspect of total network costs.

Keywords: recycling network, end-of-life vehicles, optimization of the location

1. Introduction

A growing ecological awareness in modern societies, legal regulations aiming at a reduction of waste storage and economic benefits that we can have from recycling of used products led to a situation that the creation of recycling networks has become an important issue, particularly in developed countries.

We can talk about creating of a structure of a recycling network in two cases. The first one is when a recycling network on a given area has to be built as a green field project; the other one is introducing modifications in an already existing structure. The network is built as a green field project if legal regulations on a given area force such solutions. In 2000 in the EU a directive was adopted [4] that obliges all the EU member states to provide their citizens with a vehicle recycling network

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that would guarantee each vehicle owner an opportunity to return the vehicle for processing and superimposes factors of network efficiency in the form of certain obligatory recovery levels. In the U.S. a recycling network was developed not because of the legal requirements but based on strictly economic reasons. On certain areas, manufacturers (steelworks) themselves took up the task of creating a recycling network to be able to collect vehicles from the market that are a valuable source of recyclable materials, steel in particular. The problem of optimization also takes place when we want to modify the existing network structure. This may happen if the network is insufficiently developed and has to be expanded by new entities or quite contrary – there are too many entities, which renders them unprofitable and some of them have to be closed down.

In Poland the need to create recycling networks results from the forecasts of needs related to the management of end-of-life vehicles (ELV), insufficiently developed vehicle recycling network on the level of processing entities and the need to comply with the EU requirements related to the system infrastructure.

Irrespective of the motivation for the network design, it should not be of random nature. The decision related to the entity location should consider the highest possible number of factors (technical, economic, environmental and legal). Hence, the creation of a given fragment of the network (e.g. when expanding) and a location of new entities will assure a maximization of benefits both from the point of view of the network participants and the vehicle owners not to mention other entities.

2. Literature Studies

The creation of a vehicle-recycling network belongs to a wider research area – reverse logistics. Reverse logistics is related to the creation of added value in a return path as opposed to the initial flow in the logistics processes [12]. It comprises all the elements related to the flow of goods whose owner or user does not wish to use anymore and passes it forward to the manufacturer's distribution network or another network collecting this type of product. While the optimization of entity location in forward logistics has received sufficient attention for years, the reverse logistics has been a subject if investigations for a relatively short period of time. Yet, because this area kindles much interest among the scientists, already a variety of papers have been published treating on the optimization of the location of entities participating in the recovery logistics. It is noteworthy that in the 60s and 70s of the last century the basic and actually the only criterion in the optimization of the location of entities related to the waste management was minimization of costs [1]. Only in the 80s of the last century, when the ecological awareness of the societies grew, other aspects became more important, particularly those related to the environment protection.

Even though many works treat on the optimization of the location of the recovery network entities few of them concern end-of-life vehicle recycling networks.

A model discussing the issue of location-allocation at the same time covering the issue of selection of network entity locations and material flows on the example of a German end-of-life vehicle recycling network) has been presented in the work of Schultmann et al. [11].

Mansour and Zarei [8] have set a goal to identify the sources of costs related to the obligation imposed by the UE regulations and develop a model that would include the optimization of the end-of-life vehicle recovery logistics showing the number, location and throughput of the return stations, dismantlers and the flow statistics among the entities. What makes this model different is that the modeling of the process and the recovery is done for more than one period while most of the models described in the literature assume a single stage end-of-life product processing. The use of the multi-period model allowed incorporating the differences in the end-of-life vehicles supply between the periods and included the storage costs. As a criterion of optimization the authors adopted the minimization of costs of logistics for the vehicle manufacturers and the minimization of the material flow among the entities.

The model of optimization of the location of the end-of-life vehicles recycling network entities in Mexico has been presented in the work by Cruz-River and Ertel [2]. In this model it has been assumed that the return stations are also dismantlers, i.e. the structure of the network has been simplified. Yet, the scenarios of return station locations were shown for the return of 75%, 90% and 100% of the end-of-life vehicles on a given area. The basic feature that distinguishes this model is that the locations of the regional distribution centers are not selected from among the initially set potential locations but are indicated by the model.

The above-presented works are focused on designing of a separate network for the recovery logistics. Because of the differences in the new and end-of-life streams of products rarely is it proposed to connect the recovery logistics with the new vehicle distribution network. The model designed for locating of the new vehicle distribution network entities joint with the end-of-life vehicle recycling network has been presented in work of Zarei et al. [14]. In this case the optimization is based on simultaneous minimization of costs of the forward logistics and recovery logistics and both of the logistic systems are a unity. The objective function minimizes the costs of developing of joint distribution and return entities, the costs of developing of the dismantlers and the costs of transport of end-of-life vehicles and materials. The proposed model assumes an ELV recycling network organization that meets the assumptions of the ELV directive i.e. takes the specificity of the European member states into account.

A lot more papers discuss issues related to waste other than the end-of-life vehicles. The structure of these systems is usually simpler than the ELV recycling network. In many cases (paper or glass waste) the process of dismantling does not take place at all. For other waste the dismantling is done already at the place of storage or further processing i.e. material recycling facilities. This means that in the discussed recycling network there are fewer intermediate stages and fewer recipients but there may be more collecting points (return stations).

We can, however find some analogy to the ELV recycling network. The work of Louwers et al. [7] is noteworthy here, whose subject of research was the location of recycling facilities of carpeting waste. The described structure of the recycling network was similar to the structure of the ELV recycling network as the model proposed regional initial processing centers where identification, selection segregation and preparation of waste for further processing were carried out.

3. The Elements of the Structure of the Recycling Network

For the purpose of modeling of the recycling network we assume that the structure of the recycling network is represented by a graph G, i.e.:

$$\boldsymbol{G}= <\boldsymbol{W}^R, \boldsymbol{L}^R>$$

where: $\boldsymbol{W}^{\boldsymbol{R}}$ is a set of number of entities in the recycling network and $\boldsymbol{L}^R$ is a set of the connections among the distinguished entities in this network. Hence, the arches of graph $\boldsymbol{G}$ represent the existing transport connections between the ‘hubs’ of the recycling network. For these investigations we assume that at the hubs and arches of the investigated recycling network a set of functions F_W^R and F_L^R are given, each of strict interpretation e.g. quantities of the realized tasks by the network entities, types of vehicles collected by the return stations, types of waste received by the recycling facilities, throughput potential of individual entities costs of task completion and initial expenditures on the creation of the entity [9].

Set $\boldsymbol{W}^R$ is a set of numbers of entities that play key roles for the building of the recycling network structure, that is:

- Return stations – locations that receive the ELVs by their last owners; the set of all the vehicle return stations has been marked $\boldsymbol{P}^Z$;
- Dismantlers – facilities that remove hazardous materials and consumables from the ELVs, dismantle parts for further use and dismantle parts and subassemblies for material recycling; the set of all dismantlers has been marked $\boldsymbol{S}^D$;
- Industrial shredders – facilities where the vehicle bodies after dismantling undergo shredding in order to recover metals and possibly other material fractions; the set of all industrial shredders has been marked $\boldsymbol{M}^P$;
- Material recycling facilities– facilities where waste received from the dismantlers and industrial shredders is processed; the set of all the material recycling has been marked $\boldsymbol{Z}^R$.

For these investigations we additionally distinguished set $\boldsymbol{I}^Z$ of the source of the end-of-life vehicles and set $\boldsymbol{O}^D$ of the waste generated during the treatment process.

Figure 1 presents a general model of the network that includes the relations among the listed entities in the form of physical flow of goods (ELV and waste).

The ELVs are assigned to the places of their origin i.e. the vehicle owners. The owner returns the vehicles to the return stations or directly to the dismantlers where all the ELVs, previously collected at the return stations have to go. At the dismantlers all the consumables and dangerous elements as well as parts for further use are removed from the vehicle including those for material recycling. The parts that are good for further use go directly to the sales channels and the other retrieved elements are forwarded to the recycling facilities that carry out the disposal process. The rest of the body goes to the industrial shredders. There, in the shredding process we obtain metal, non-metal and shredder residue. Metal fractions go the processing facilities and the rest is combusted with energy recovery or stored at the disposal sites.

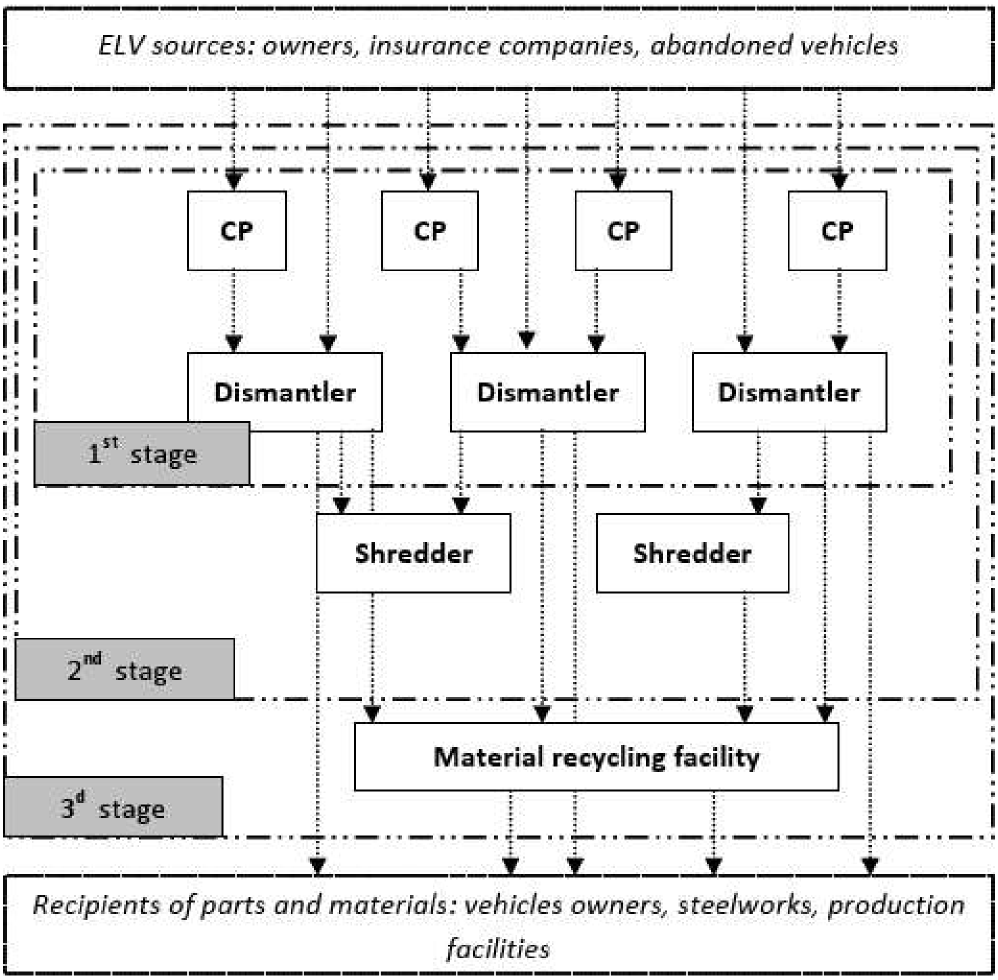

Fig. 1. Elements of the recycling network and the connections among them

While performing the modeling of a recycling network we can focus on a selected type of entities or simultaneously optimize the location of several types of entities belonging to the network. Hence, modeling of the recycling network may pertain to different areas. The simplest models of the network pertain exclusively to the location of the dismantlers and possibly to the return stations. In the next stage of the modeling the location of the industrial shredders is included in the decision variables. The most complex model that comprises all the entities directly related to the ELV recycling network is a model optimizing all – the return stations, the dismantlers, the industrial shredders and the material recycling facilities. In real application we do not have such complex models due to the difficulty with collecting all the necessary information related to the characteristics of such a varied group of entities. Besides, there is a difficulty finding an optimum solution for the problem formulated on such a large scale.

4. The Factors Influencing the Selection of the Entity Location

When deciding about the location we must take several factors into account that result from the characteristics of the entities and the conditions that the recycling network must meet on a given area. The characteristics of the entities refer to the technical aspects such as throughput strictly related with the equipment and applied technology and the economic aspects determining the profitability of the activity.

For the return stations the factors that influence the selection of the location are:

- distance between the ELV source and the return stations and dismantlers,
- minimum number of end-of-life vehicles received at the return station,
- cost of transport of one ELV.

The return station has to be located sufficiently far from the dismantlers to make its existence reasonable. If the dismantler is located in the vicinity of the return station and the source of the vehicle, then from the point of view of the cost minimization it will be more profitable to forward the vehicles directly from the source to the dismantlers circumventing the return stations. Modeling the recycling network for the Polish conditions, the return station or the dismantler cannot be based farther than 50 km from the ELV source, which is imposed by the legal regulations in Poland. The cost of transport refers to the distance between the source and the return station, the source and the dismantler and the return station and the dismantler. We can also modify the model and introduce an assumption that the transport from the ELV source to the return station is at the expense of the vehicle owner, which also occurs in reality.

Because at the return stations there is no activity related to vehicle disposal and the only activity is vehicle identification and documents revocation, the characteristics do not include the throughput thereof. Yet, the minimum number of vehicles that the station has to receive per annum for break even has been given.

The consequence of lack of operations related to the processing of ELVs is that the total costs of the return station operations related to the ELV processing (KC_z) are equal to the overheads (KS_z). The overheads of the return stations are such components as: vehicle procurement costs (K_{po}), equipment depreciation (K_{am}), wages (K_{wp}), utilities (K_{me}) and other costs (K_p), i.e.:

$$KC_z = KS_z = K_{po}(z) + K_{am}(z) + K_{wp}(z) + K_{me}(z) + K_p(z)$$

For a dismantler, when selecting a location the following will be important:
- distance between the source, the return station and the dismantler,
- cost of a single ELV transport,
- station throughput,
- station break even point that determined the minimum throughput.

In relation to the return stations the station throughput comes up that determines the maximum number of vehicles that the station can process in one year.

In the case of the dismantlers the total costs of operations (KC_s) are the overheads (KS_s), whose level depends on the assumed throughput and variable costs (KZ_s) being a linear function of the number of ELVs processed at the station. Hence, the function of the total costs we can notate as follows:

$$KC_s = KS_s + KZ_s$$

$$KS_s = K_{po}(s) + K_{am}(s) + K_{wp}(s) + K_p(s)$$

$$KZ_s = JKZ_s \cdot n_s$$

$$KC_s = K_{po}(s) + K_{am}(s) + K_{wp}(s) + K_p(s) + JKZ_s \cdot n_s$$

The station overheads are the costs of procurement of the premise, salaries, equipment depreciation and other costs (insurance, utilities, promotional activity, accounting). The cost of procuring of the object can be expressed as the costs of lease or depreciation of a building for which the station has a title. The variable cost is a product of unit variable costs (JKZ_s) and the ELV number processed in s-th station (n_s). The amount of the variable costs is most influenced by the consumption of energy and waste storage.

Based on the actual data collected within the realization of the research project on the location of ELV entities [10] the function of total costs can be expressed as a function of the number of processed vehicles at the dismantlers.

$$y = -319{,}93n_s^4 + 7436{,}2\ n_s^3 - 35151n_s^2 + 125880n_s + 159094$$

Analogically, the factors influencing the location of the industrial shredders will be similar, only the cost of transport will pertain to the unit of the waste cargo. Hence, the location of the industrial shredders will be influenced by:
- distance among the shredder, the dismantler and the recycling facilities,

- cost of transport of 1 kg of waste,
- shredder throughput,
- break even point of the shredder that determines the minimum throughput.

The total costs of the shredder operation (KC_p) can be notated (similar to the dismantlers) as a sum of the overheads (KS_p) whose level depends on the assumed throughput potential and dismantling costs (KZ_p) being a linear function of the amount of processed waste (m_p). The function of total costs we can express as follows:

$$KC_p = KS_p + KZ_p$$

$$KS_p = K_{wo}(p) + K_{am}(p) + K_{wp}(p) + K_p(p)$$

$$KZ_p = JKZ_p \cdot m_p$$

$$KC_p = K_{wo}(p) + K_{am}(p) + K_{wp}(p) + K_p(p) + JKZ_p \cdot m_p$$

The kinds of overheads for the shredders and the dismantlers are the same. The variable costs constitute the energy consumption, the cost of obtaining scrap metal and storage costs.

The function of total costs depending on the mass of the processed waste we can notate as follows [10]:

$$y = 609364m_p^4 - 1E{+}06m_p^3 - 7E{+}06\ m_p^2 + 5E{+}07m_p - 1E{+}07$$

Eventually, the selection of the location of the material recycling facilities will depend on:

- distance among the recycling facilities, the stations and the industrial shredders,
- cost of transport of 1 kg of waste,
- throughput potential of the faculties,
- kind of processed waste.

The recycling facilities are different in terms of what they process and these characteristics have to be taken into account when selecting a given location. The minimum throughput has not been given as the recycling facilities, apart from automotive junk, can also receive waste that comes from other sources, which guarantees an excess of revenues over the costs.

5. Optimization Criteria

For the creation and optimization of the structure of the recycling network it is necessary to use decision aiding optimization methods. Picking the optimum solution requires determining a decisive criterion that is the indicator of the quality of the solution (the solution that is the optimum one from a set of feasible decisions). The optimization criterion is a reflection of the preference function of the entity making a decision. Depending on the number of preference functions included as partial functions of the criterion, the optimization tasks can be divided into single and multi criteria ones.

Single criterion optimization tasks are more frequently used because of their simpler process of formation and simpler realization as well as quicker and easier finding of optimum solutions.

The most frequent objective functions in single criteria optimization tasks are:
- minimization of costs,
- maximization of profit,
- minimization of processes duration.

In the case of complex processes (recycling network belongs to such processes) irrespective of the subject of optimization (adapting of the infrastructure to the needs, entity locations, efficiency) it is difficult to set a single criterion that will be satisfactory for all the interested parties. It is because of the fact that the preferences of government administration, vehicle owners, vehicle manufactures and recycling network participant are divergent.

A growing awareness of the society and a comprehensive implementation of sustainable development concept in developed countries have resulted in that the designing of a recycling network cannot only be based on the mere desire of the entities to participate in that network and their individual profit account. Such entities make their decisions exclusively based on the profitability analysis, which should not be the only decisive criterion in terms of the entity location.

Many participants that are interested in the functioning of a recycling network translate into a variety of points of view. Each of them attempts to extremize their individual benefit. The formation of a recycling network is thus a complex multi aspect decision process, related to decision making under condition of limited financial resources as well as limited technical resources in terms of number and type.

Multicriteria approach towards decision aiding assumes a minimization or maximization of the objective function composed of many partial criteria. This does not change the fact that even for complex systems we can build (and it is done that way) single criterion optimization tasks, often being a prelude to the multlicriteria modeling.

Formulating multicriteria optimization tasks requires determining the set of feasible solutions and the set of partial criteria that transform the set of solutions into the set of quality evaluations. In the mathematical aspect the set of feasible solutions is expressed in a form of a system of equations and inequalities.

In multicriteria tasks there is no decision (solution or action) that is the best one from all points of view at the same time. The notion ‘optimum’ in this case has a different meaning compared with classic optimization theory. An optimum realization of a single objective most often results in a limping of at least one of the other tasks. The decision is thus made in the context of simultaneous realization of all the distinguished partial functions of the criteria. Solving multicriteria tasks leads to determining of the best alternative while considering various interactions within the set of constraints reaching acceptable level of the set of criteria so that the decision maker is most satisfied.

The objective function we can thus present as a set of measurable evaluation criteria where K denotes the number of partial functions of criteria:

$$F = \{f(1), f(2), \ldots, f(k), \ldots, f(K)\}$$

while the individual partial functions are assigned weights reflecting the relative importance of the criterion. The weights are expressed as certain values.

In general, the problem of multicriteria optimization can be notated in the following mathematical form [6]:

$$\mathrm{F}{=}{<}\, f_1(\mathrm{x}),\ f_2(\mathrm{x}),\ldots,f_k(\mathrm{x}),\ldots,f_K(\mathrm{x}){>}\rightarrow \max$$

with the constraints:

$$a_i(x) \leqslant b_i \quad i = 1, \ldots, m$$

the set of feasible solutions we can then express as a set of elements x:

$$D^{dop} = \{x : a_i(x) \leqslant b_i, i = 1, \ldots, m\}$$

while the corresponding objective function is defined as:

$$D_f = \{F : F = < f_1(x), f_2(x), \ldots, f_k(x), \ldots, f_K(x) >, \quad x \in D^{dop}\}$$

In multicriteria modeling we can have two or more partial functions. In two criteria tasks the most frequently used partial criteria functions are as follows [13]:
- minimization of costs and minimization of process duration,
- minimization of costs and maximization of geographical area coverage,
- minimization of costs and minimization of negative impact on the surrounding environment,
- minimization of costs and minimization of distance among the elements.

The authors (Current et al. [3]), when reviewing the works in multi objective decision making divided the multicriteria problems into four groups depending on the type of the objective function. Hence, the objective function can be divided into functions related to the problem of:
- Demand coverage;
- Dealing costs;
- Profitability;
- Environmental issues.

In the above groups of functions we can distinguish objective functions used in the selection of location of entities that belong to the recovery network. These are [5,13]:
- Minimization of costs

Partial criteria can comprise the minimization of both the overheads and variable costs. In the overheads we most often include the initial investment (the cost of the initiation of the activity) expressed in depreciation and the cost of continuing of the activity independent of the production size (expressed in the quantity of services, size of production, amount of processed waste). Variable costs constitute: transport, production, maintenance costs, employees, distribution, warehousing, environmental costs (e.g. those related to the neutralization of waste). If the objective function minimizes the total costs then this cost will comprise all the said costs. In some cases also the dealing costs are minimized.

- Minimization of environmental risks

Minimization of environmental risks denotes the minimization of the transport risk, waste storage and processing as well as minimization of side effects (noise, toxic emissions).

- Maximization of coverage

The coverage can have a geographical aspect (distances, area), time-related aspect or quantity-related aspect (demand coverage). Within this group the most frequently used is the maximization of distance and population. Into this group we can also include the criterion of equity and dispersion as this preference also refers to the problem of coverage but in an equitable way.

- Maximization of the service quality and the efficiency of the process

These criteria, among others, cover: maximum use of the infrastructure or the maximization of the indexes related to the range of rendered services.

- Maximization of profit

This refers particularly to the maximization of the net profit, maximization of the return on investment, maximization of the revenues or maximization of profitability (the difference between the revenues and the expenses).

- Other criteria

Among the partial functions of the criterion we can see other preferences that do not fall within the above-mentioned groups e.g. those related to the access to the resources, political or social risks.

6. General Formulation of the Optimization Task

Below an example formulation of an optimization task will be presented, whose subject is the optimization of the location of entities of an ELV recycling network.

The assumptions to the creation of the network are as follows:

- the optimization pertains to the return stations, dismantlers and industrial shredders,
- the selection of the final location is done from among the indicated admissible locations,
- all returned vehicles have to be subsequently forwarded to the dismantlers,

- the operating costs of the entities are overheads and variable costs, but for the return stations we only distinguish the overheads,
- the objective function reflects the preferences of the participants of the recycling network,
- it has been assumed that the main objective of the entities is the minimization of the investment costs the operating costs,
- in order to obtain the solution to the optimization task we need to know the following quantities:
  - initial expenditure necessary to open the return station, the dismantlers and the industrial shredders,
  - operating costs of the return stations, dismantlers and the industrial shredders (the costs are divided into overheads and variable costs),
  - unit transport costs of ELVs and the transport costs of waste,
  - distances among: 1) the sources, the potential return stations and the dismantlers, 2) the return stations and the dismantlers, 3) the dismantlers, the industrial shredders and the recycling facilities and 4) the industrial shredders and the recycling facilities.
- the set of potential locations of the return stations, dismantlers and industrial shredders is given. We also know the location of the material recycling facilities.

The decision variables are the location variables indicating the location of the analyzed entities where:

x_s– denotes a binary variable that equals 1 if locating the dismantler in a s-th location or 0 in an opposite case

y_z– denotes a binary variable that equals 1 if locating the return station in a z-th location or 0 in an opposite case

z_p – denotes a binary variable that equals 1 if locating the industrial shredder in a p-th location or 0 in an opposite case

During the tasks-solving process the following quantitative variables are also determined:

n_{iz} – the number of ELVs transported from the i-th source to the return station in z-th location,

n_{is}– the number of ELVs transported from i-th source to the dismantler in the s-th location,

n_{zs} – the number of ELVs transported from the return station located in the z-th to the station in the s-th location,

$m_{sp}(o)$ – the mass of the o-th waste transported from the station located in the s-th location to the shredder in the p-th location,

$m_{sr}(o)$ – the mass of the o-th waste transported from the station located in the s-th location to the recycling facility in the r-th location,

$m_{pr}(o)$ – the mass of the o-th waste transported from the shredder located in the p-th location to the recycling facility in the r-th location.

The objective function assumed in the task reflects the total costs of creating and functioning of the recycling network that are constituted by such costs as:

- the initial expenditure necessary for the creation of return stations ($\mathrm{NI_z}$), dismantlers ($\mathrm{NI_s}$) and industrial shredders ($\mathrm{NI_p}$),
- operating costs of the return stations, dismantlers and industrial shredders,
- the costs of transport of ELVs that are the sum of the unit costs of the ELV transport ($\mathrm{JT_{SWE}}$), the number of the vehicles transported between the entities and the distance between the sources and the return stations ($\mathrm{d_{iz}}$), the sources and the dismantlers ($\mathrm{d_{is}}$) and the return stations and the dismantlers ($\mathrm{d_{zs}}$),
- the costs of transport of waste between the entities that are the sum of unit costs of transport of waste ($\mathrm{JT_o}$), the mass of waste and the distance between the entities i.e. the dismantlers and the shredders ($\mathrm{d_{sp}}$), the dismantlers and the recycling facilities ($\mathrm{d_{sr}}$) and the shredders and the recycling facilities ($\mathrm{d_{pr}}$).

The total costs will be minimized; hence the objective function will have the form:

$$
\begin{aligned}
f(\mathbf{X},\mathbf{Y},\mathbf{Z}) = {} & \sum_{z\in\mathbf{P^Z}} NI_z \cdot y_z + \sum_{s\in\mathbf{S^D}} NI_s \cdot x_s + \sum_{p\in\mathbf{M^P}} NI_p \cdot z_p + \sum_{z\in\mathbf{P^Z}} KS_z \cdot y_z + \sum_{s\in\mathbf{S^D}} KS_s \cdot x_s + \sum_{p\in\mathbf{M^P}} KS_p \cdot z_p + \\
& + \sum_{s\in\mathbf{S^D}} JKZ_s \cdot \left(\sum_{i\in\mathbf{I^Z}} n_{is} + \sum_{z\in\mathbf{P^Z}} n_{zs} \right) + \sum_{p\in\mathbf{M^P}} JKZ_p \cdot \sum_{s\in\mathbf{S^D}} m_{sp} + \\
& + JT_{SWE} \cdot \left(\sum_{i\in\mathbf{I^Z}} \sum_{z\in\mathbf{P^Z}} n_{iz} \cdot d_{iz} + \sum_{i\in\mathbf{I^Z}} \sum_{s\in\mathbf{S^D}} n_{is} \cdot d_{is} + \sum_{z\in\mathbf{P^Z}} \sum_{s\in\mathbf{S^D}} n_{zs} \cdot d_{zs} \right) + \\
& + JT_O \cdot \sum_{o\in O^{\mathbf{D}}} \left[\sum_{s\in\mathbf{S^D}} \sum_{p\in\mathbf{M^P}} m_{sp}(o) \cdot d_{sp} + \sum_{s\in\mathbf{S^D}} \sum_{r\in\mathbf{Z^R}} m_{sr}(o) \cdot d_{sr} + \sum_{p\in\mathbf{M^P}} \sum_{r\in\mathbf{Z^R}} m_{pr}(o) \cdot d_{pr} \right] \to \min
\end{aligned}
$$

The creating of the recycling network requires a variety of constraints to be taken into account that refer to:

- Treatment of all ELVs from ELVs sources

$$\sum_{i\in\mathbf{I^Z}} \sum_{z\in\mathbf{P^Z}} n_{iz} + \sum_{i\in\mathbf{I^Z}} \sum_{s\in\mathbf{S^D}} n_{is} = N$$

- Minimum throughput that guarantees profitability

$$\forall z \in \boldsymbol{P^Z} \quad \sum_{i\in\mathbf{I^Z}} n_{iz} \geqslant n_{z\,\mathrm{min}} \cdot y_z$$

$$\forall s \in \mathbf{S^D} \quad \sum_{i\in\mathbf{I^Z}} n_{is} + \sum_{z\in\mathbf{P^Z}} n_{zs} \geqslant n_{s\,\mathrm{min}} \cdot x_s$$

$$\forall p \in \mathbf{M^P} \quad \sum_{s\in\mathbf{S^D}} \sum_{o\in O^{\mathbf{D}}} m_{sp}(o) \geqslant m_{p\,\mathrm{min}} \cdot z_p$$

- Maximum throughput potential

$$\forall s \in \mathbf{S^D} \sum_{i\in\mathbf{I^Z}} n_{is} + \sum_{z\in\mathbf{P^Z}} n_{zs} \leq n_{s\,\mathrm{max}} \cdot x_s$$

$$\forall p \in \mathbf{M^P} \forall o \in O^{\mathbf{D}} \sum_{s \in \mathbf{S^D}} m_{sp}(o) \le m_{p\,\mathrm{max}}(o) \cdot z_p$$

$$\forall r \in \mathbf{Z^R} \forall o \in O^{\mathbf{D}} \sum_{s \in \mathbf{S^D}} m_{sr}(o) + \sum_{p \in \mathbf{M^P}} m_{pr}(o) \le m_{r\,\mathrm{max}}(o)$$

- The keeping of the flow continuity

$$\forall z \in \mathbf{P^Z} \sum_{i \in \mathbf{I^Z}} n_{iz} = \sum_{s \in \mathbf{S^D}} n_{zs}$$

$$\forall s \in \mathbf{S^D} \forall o \in O^{\mathbf{D}} \left(\sum_{i \in \mathbf{I^Z}} n_{is} + \sum_{s \in \mathbf{S^D}} n_{zs} \right) \cdot \alpha(o) = \sum_{p \in \mathbf{M^P}} m_{sp}(o) + \sum_{r \in \mathbf{Z^R}} m_{sr}(o)$$

$$\forall p \in \mathbf{M^P} \forall o \in O^{\mathbf{D}} \sum_{s \in \mathbf{S^D}} m_{sp}(o) = \sum_{r \in \mathbf{Z^R}} m_{pr}(o)$$

- Location variables that have to assume binary values, where 1 denotes a selection of a given location and 0 giving up of this location

$$\forall s \in \mathbf{S^D} x_s \in \{0, 1\}$$

$$\forall z \in \mathbf{P^Z} y_z \in \{0, 1\}$$

$$\forall p \in \mathbf{M^P} z_p \in \{0, 1\}$$

- The outstanding variables must be natural numbers or real positive numbers

$$\forall i \in \mathbf{I^Z} \forall z \in \mathbf{P^Z} \quad n_{iz} \in \mathcal{N}$$

$$\forall i \in \mathbf{I^Z} \forall s \in \mathbf{S^D} \quad n_{is} \in \mathcal{N}$$

$$\forall z \in \mathbf{P^Z} \forall s \in \mathbf{S^D} \quad n_{zs} \in \mathcal{N}$$

$$\forall s \in \mathbf{S^D} \forall p \in \mathbf{M^P} \forall o \in O^{\mathbf{D}} \quad m_{sp}(o) \in \mathcal{R}^+$$

$$\forall s \in \mathbf{S^D} \forall r \in \mathbf{Z^R} \forall o \in O^{\mathbf{D}} \quad m_{sr}(o) \in \mathcal{R}^+$$

$$\forall p \in \mathbf{M^P} \forall r \in \mathbf{Z^R} \forall o \in O^{\mathbf{D}} \quad m_{pr}(o) \in \mathcal{R}^+$$

Besides, we have to take into account the constraints related to the maximum distance between the source and the return stations (or alternatively the source and the dismantler)

$$\left| d_{iz} \right| \cdot y_z \le \max\{d'_{iz}\}, \quad \forall\, z \in \mathbf{P^Z}, \quad \forall\, \mathrm{i} \in \mathbf{I^Z}$$

The above formulated optimization task enables an optimum selection of the locations of the key participants of the end-of-life vehicle recycling network (return stations, dismantlers and industrial shredders) in terms of total costs of the creation and keeping of the network. The selection takes place from the indicated set of admissible locations of the infrastructure elements. The solving of the task also provides the answer to the question of the material flow among the individual network entities.

In the material flows, the size of the streams of waste to be disposed of at the disposal sites has not been taken into account.

7. Conclusions

The design of recycling networks requires appropriate decision aiding tools. The specificity of and the expectations from the waste management system including end-of-life vehicles result in that their location and functioning have to be based on informed decisions related to the following:

- technical aspects of vehicle recycling,
- economic aspects (the problem of network profitability),
- legal aspects (requirements for the network organization),
- social (network accessibility, nuisance (annoyance) related to the activity of some entities),
- environmental aspects (the necessity of reducing negative impact of vehicle on the environment and the minimization of such negative impact of the networks themselves).

Taking into account so many factors complicates the decision making process, hence there is the need to develop dedicated tools that aid the decision making process related to the recycling networks. Despite a recent growing interest in the methods of multi criteria decision aiding, single criterion modeling is also used in the optimization of the network entity location, often as a prelude to the application of multicriteria ones. In the optimization tasks most often the objective function requires that the costs are minimized and the constraints refer mainly to the balancing of the flows, possibilities of waste processing, storage and non-negativeness of the variables.

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